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Energy Payback Time and Environmental Assessment on a 7 MW Photovoltaic Power Plant in Hamedan Province, Iran

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ABSTRACT

Nowadays, environmental protection and efforts to reduce pollution, caused by industrial activities, on one hand, and research on finding new and improved energy supply options on the other, have become one of the major concerns of governments around the world. In recent years, photovoltaic (PV) systems, due to their proved potential are rapidly developed in most parts of the earth. The objective of this study, is to estimate the amount of CO_2 emission reduction by implementing a 7 MW PV power plant. The location of this power plant is in the north of Hamedan province, Iran. Moreover, the amount of not consumed fossil fuel were measured. Finally, it is found that the total reduction of 134050 t CO_2 will be achieved when PV power plant is used compared to a natural gas one, during 25 years. Moreover, in this paper, the energy payback time (EPBT) and the Energy Yield Ratio (EYR) are calculated. The results show that EPBT is about 5.5 years and EYR of mentioned PV power plant is more than 4.2.

1. Introduction

Energy and Environment are important concepts, which always should be explored together. In other words, we cannot speak about optimization or innovation of an energy, without any attention to its positive and negative impacts on environment. In recent years, Because of the pollution caused by traditional power plants consuming fossil fuels, governments have tend to use renewable and sustainable methods to produce power, symmetrical to their geographical and climate conditions. In December 11th, 1997, an international protocol was assigned by the most of the countries with the main aim of stabilization of greenhouse gas (GHG) concentration in the atmosphere. This protocol, known as Kyoto protocol, obliges countries to reduce the emission of GHGs, the main factor of global warming. More details on the performance of some countries in Kyoto protocol is available in [1].

The renewable capacity has experienced a sustained, globally strong growth over the last few years. Since the beginning of this decade, it has been steadily grown at about 8-9% annually, which is more than double the average growth for non-renewables [2].

Iran has a huge potential in most kinds of renewable energies, especially in wind, hydro and solar energies. The mentioned potentials and moreover the degradation ratio of fossil fuels resources, leads to increase the governmental supports for investors of renewable energies. So that, the investment of different kinds of sustainable energy generation is growing rapidly. More information of this area can be found in [3, 4].

There are a wide range of researches on photovoltaic field. Studies on cooling the PV modules in

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order to improve efficiency [5-9], sensitivity analysis [10], maximum power point tracking systems [11, 12], exergy analysis [13], residential PV systems [14, 15], photovoltaic tracking systems [16], etc. Energy payback time (EPBT) and environmental impacts of using PV power plants are the other fields which are considered recently by scholars.

Alipara et al. [17] have investigated the amount of reduction in GHG emission, caused by renewable energies in different seasons in Italy. Wang et al. [18] predicted costs and CO_2 emission reduction of PV power plants in China. In that study, the large scale of photovoltaic power plants, residential photovoltaic systems and distributed electricity generation, were investigated for each province separately. It was predicted that in 2020, the initial cost of a PV power plant will be about 60% less than 2010.

Both EPBT and CO_2 emission have been assessed by Hogue et al. [19] for solar home systems in Bangladesh. They showed that small solar home systems which operated by 40-85 W PV modules, had an EPBT of 6.91 to 7.8 years. Furthermore, it has been demonstrated that about 1.4 million solar home systems in Bangladesh (until February, 2013), caused reduction of about 0.8 million tons of CO_2 annually. Peng et al. [20] focused on sustainability and environmental performance of generating electricity by PV power plants. Five different common PV systems were investigated in their study. They showed that the CdTe thin film technology had the lower EPBT and GHG emission compared with the others.

Adam and Apadin [21] were studied on return investment of GHG diffusion of a 500 kW PV power plant, located in Gaziantep city, Turkey. Gaziantep is placed in south of Turkey, with average solar irradiation of 1460 kWh/m^2 per year and sunshine of about 2993 hours, annually. That research was carried out by RETScreen software and showed the mentioned power plant has financial payback period of 5.6 years. Moreover, it has been demonstrated that establishing this PV power plant will prevents of 331.4 tons of CO_2 emission annually. Gharibshahi et al. [22] had an investigation of a 100 kW PV power plant in Semnan, Iran. The analysis was done by PVSYST software and reported that the construction of this power plant could prevent the entry of 171 tons of CO_2 into the environment during its lifetime. Sanni and Mohammed [23] analyzed a residential PV system by RETScreen software. In that study, the financial estimation has been performed as a comparison of a PV system vs grid electricity. This research was done in the climate of Ado-Ekiti, Nigeria. Finally, it was shown that using of a 2 kW residential PV system is more economical.

In literature review, there is no published paper found, which CO_2 emission reduction, EPBT and EYR of a real PV power plant. So, in this study, the environmental assessment of establishing a 7 MW photovoltaic power plant has been performed in Hamedan, Iran. RETScreen software was used to achieve this aim. Moreover, both EPBT and EYR, which are important energetic parameters, were calculated for mentioned power plant.

2. Solar Energy potential in the world and Iran

Installed capacity of renewable energies have a significant mutation in recent years. So that, only in 2018, more than 170 GW was added to global installed capacity of renewables. By considering the mentioned additional capacity, the global installed capacity of all kinds of renewable energies exceeded of 2,350 GW. Solar and wind energies had important role to achieve this success and about 84 % of mentioned growth is depends on these energies. Installed capacity of renewable energies in the Asia, exceed of 1,018 GW to the end of 2018 [2]. China, India, Japan, Vietnam and Iran are ranked first to fifth, respectively in this continent and Iran has the first rank in the Middle East.

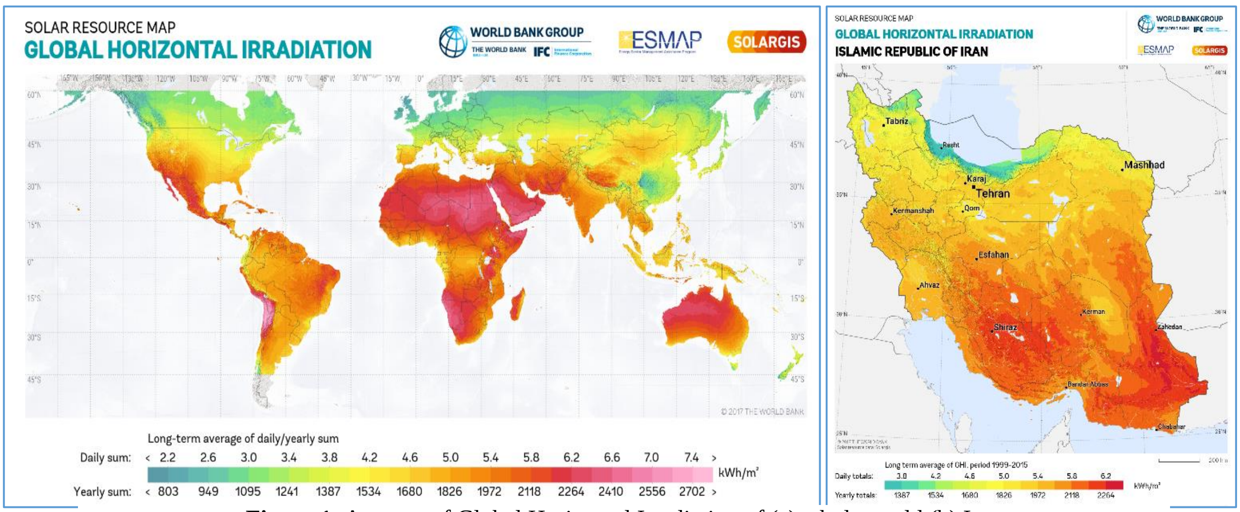

Figure 1. Average of Global Horizontal Irradiation of (a) whole world (b) Iran

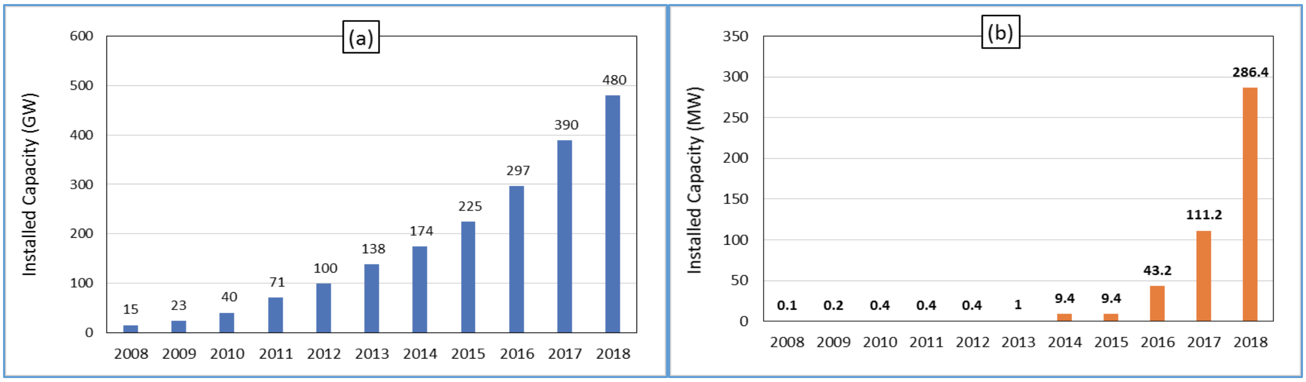

Figure 2. Installed capacity of photovoltaic power plants in (a) world (b) Iran [2]

The use of sunlight in order to generating power, is not justifiable in all countries. Figure 1 (a) shows the average of Global Horizontal Irradiation (GHI) of the earth, per year. According to this map, it is clear that Iran has a suitable situation and great solar irradiation, compared with the other regions (Figure 1 (b)). Iran has the average solar radiation of 5.5 kWh/m^2 per day. Moreover, there are 300 sunny days in more than two-thirds of Iran's area.

The north area of Iran, has GHI of about 1200 kWh/m^2 per year, which is the lowest, and in south eastern area, we have GHI of about 2300 kWh/m^2 per year, which is the highest. Due to this significant potential, domestic and foreign investors tend to establish PV power plants in Iran. So that, until the end of 2018, the amount of 286.4 MW photovoltaic power plants have been implemented. In Figure 2 the rapid rate of establishing PV power plants in Iran has been illustrated.

3. Case study description

A 7 MW photovoltaic power plant of Beshik-Tappeh, near Kabudarahang city, in Hamedan province, Iran, was implemented by an investment of about 8 million Euros, on an area of 14 hectares and got started from February 2019. Beshik-Tappeh has the average GHI of 5.05 kWh/m^2, where the minimum and maximum of GHI are 2.44 kWh/m^2 (December) and 7.63 kWh/m^2 (June), respectively. The exact location of Beshik-Tappeh village is depicted in Figure 3. Solar tracking system was used in this PV power plant, so that, 6 MW has fixed structure and remaining 1 MW has solar tracking system. Yingli Solar photovoltaic modules with nominal power of 350 W were used. Also, KACO inverters were used to convert the generated electricity from DC to AC. The technical and electrical parameters of PV modules and inverters have been presented in Table 1 and Table 2, respectively.

Generally, this PV power plant could generate about 1,254,147,300 kWh electricity per year. But there are some miscellaneous losses which decrease the calculated value. For example, the presence of dust or snow on the PV modules, mismatch and wiring losses, damaged in connectors between modules, etc. in this research, the sum of all these losses are considered 16 %.

Figure 3. The exact location of Beshik-Tappeh PV power plant

Table 1. Techno-electrical parameters of PV modules

PV module	
Manufacture / Country	Yingli Solar / China
Nominal Power (w)	350
Efficiency (%)	17.5
Type	Multi-crystalline Si
Number of cells	72 Cell
Temperature coefficient at max power (%/°C)	-0.38
Dimension (mm)	1960/992/40
Weight (kg)	22

Table 1. Techno-electrical parameters of Inverter

Inverter	
Manufacture / Country	KACO / Germany
Nominal Power (kw)	50
Efficiency (%)	98.5
Number of grid phases	3
Working temperature range (°C)	-20 to +60
Weight (kg)	71

4. Methodology

There are various softwares to analysis different types of power plants from different viewpoints. RETScreen is one of these common softwares, which was designed by the Department of Natural Resources of Canada. RETScreen can evaluate different kinds of power plant e.g. photovoltaic, wind energy, solar thermal power, gas turbine, hydro turbine, etc. from financial, GHG emission, cost and even the risk of investment viewpoints. In this paper, the RETScreen software is used in order to estimate the CO_2 emission reduction and compare the PV power plant with a gas turbine power plant. Another concept which is considered in this paper is EPBT and EYR. These concepts will describe in the section of 5.2.

5. Results and discussion

5.1. Mitigation of CO_2 emission

The reduction of CO_2 as an important gas of GHGs depends strongly on the location the PV power plant is located. Three parameters which are important and depend on the location of the power plant are as follows: (1) fuel types of non-renewable power plant like: natural gas, gas oil, coal and so on, (2) fuel composition which is different in various countries, (3) GHI of the location. According to the two first parameters, for different countries, an emission factor is defined for various types of fuel. For Iran, these factors are considered as 0.481 t CO_2/MWh and 0.902 t CO_2/MWh, for natural gas and gas oil, respectively. The GHG emission factor for many countries can be found in [24]. Table 3, represents annual emission reduction of CO_2 and also the amount of barrels of crude oil and liters of gasoline not consumed, by implementing a 7 MW photovoltaic power plant in Hamedan province. By considering 25 years lifetime of this power plant, the total reduction of about 126,314 t CO_2 will be achieved, compare with a natural gas power plant.

Ito et al. [25] have reported the degradation ratio of 0.5 percent per year, in efficiency of crystalline silicon cells. By this estimation, mitigation of CO_2 emission for the whole lifetime of 25 years, is presented in Table 4.

Table 2. CO_2 emission reduction of 7 MW PV power plant (Beshik-Tappeh, Hamedan, Iran)

Fuel type	Natural gas	Oil
CO_2 emission factor (t CO_2/MWh)	0.481	0.902
Annual CO_2 emission reduction (t CO_2)	5,362.3	10,068.4
Barrels of crude oil not consumed	12,470.4	23,415
Liters of gasoline not consumed	2,304,101.4	4,326,132

Table 3. CO_2 emission reduction of 7 MW PV power plant of Beshik-Tappeh, during its lifetime

Fuel type	Natural gas	Oil
Annual CO_2 emission reduction (t CO_2)	126,314.1	237,170.7
Barrels of crude oil not consumed	293,752.1	551,562.6
Liters of gasoline not consumed	2,304,101.4	101,906,155.2

5.2. Energy payback time

Energy Payback Time (EPBT), shows how long it takes for a power plant (in this paper, photovoltaic power plant) to generate the same amount of energy consumed to produce all its components.

$$EPBT = \frac{E_{input} + E_{BOS}}{E_{output\ (annual)}} \tag{1}$$

The nominator of equation (1) introduces the total of required energy for producing all components of a power plant. Some scholars, put E_{Gross} instead of this summation in them papers [25].

The definition of the three terms in equation (1) is as follows:

$\boldsymbol{E_{input}}$, is the required energy for manufacturing a square meter of PV module, which is calculated in MJ/m^2. E_{input} is divided to several portions illustrated in Table 5 with details. According to Table 5, 4600 MJ energy is required to produce one square meter PV module. Exact dimensions of a 350 W PV panel, was given previously in Table 1. Therefore, the area of each module is:

$$1.960\ m \times 0.992\ m = 1.944\ \ m^2.$$

In the Beshik-Tappeh PV power plant, the number of 20,000 modules have been used. So, the total area of all PV panels is: $20{,}000 \times 1.944\, m^2 = 38{,}880\, m^2$. Hence,

$$4{,}600\, \frac{MJ}{m^2} \times 38{,}880\, m^2 = 178{,}848{,}000\, MJ$$

energy was consumed in order to produce PV modules of this power plant.

Table 4. Required Energy to produce a PV module

Process	Energy requirement (MJ/m^2)
Silicon winning & purification	2200
Silicon wafer production	1000
Module encapsulation materials	200
Cell processing	500
Overhead operations and equipment manufacture	500
Module aluminium frame	400
Total	**4600**

According to Table 5, the energy required for production of crystalline silicon module is:

$$2{,}200\, \frac{MJ}{m^2} + 1{,}000\, \frac{MJ}{m^2} = 3{,}200\, \frac{MJ}{m^2}.$$

This amount is about 69% of the total manufacturing energy consumption of a PV module.

$\boldsymbol{E_{BOS}}$, is the required energy for balance of system (BOS), which includes the required energy of other components of a photovoltaic power plant, except PV modules, e.g. cabling, inverter and structure. For off-grid PV systems, the require energy of batteries and charge controllers should be considered too. E_{BOS} , equals to 1800 MJ/m^2 and 700 MJ/m^2 for ground-mounted and rooftop PV power plants, respectively [26]. Obviously, E_{BOS} for ground mounted is significantly greater than the rooftop. This difference exists because of more aluminum needed for ground mounted types. So, in this case study, $1{,}800\, \frac{MJ}{m^2} \times 38{,}880\, m^2 = 69{,}984{,}000\, MJ$ energy was consumed for different parts of BOS.

$\boldsymbol{E_{output\ (annual)}}$, is the annual output energy generation of the power plant. This quantity is directly related to the location of the power plant. Obviously, the more intensity and time irradiation, the more power generation and leads to decrease the EPBT. To calculate this output energy, we should first evaluate the annual power generating of this PV power plant, which is computed as 12,541,473 kWh/year. We know that 1 kWh equals to 3.6 MJ. So, $E_{output\ (annual)}$ for this study is calculated as: 45,149,302.80 MJ/year.

Note that all the above quantities depend on the technology level. As an example, Peng et al. [20], have reported the mitigation of 10,000 MJ/m^2 in 1990 to 3,000 MJ/m^2 in 2010 for module manufacturing processes. Therefore, the EPBT for Beshik-Tappeh power plant, could be calculated as follows:

$$EPBT = \frac{E_{input} + E_{BOS}}{E_{output\ (annually)}} = \frac{178{,}848{,}000 + 69{,}984{,}000}{45{,}149{,}302.80} = 5.51\ \ years$$

So, for this case study, in order to generate the same amount of energy as the primary consumed energy, 5.51 years is needed. By considering 25 years as the lifetime of a PV power plant, 5.51 years is 22% of its lifetime.

5.3. Energy Yield Ratio (EYR)

The Energy Yield Ratio (EYR) determines the ratio of energy generated by the power plant over its lifetime to the total energy used to produce the power plant's equipment, which is presented by following equation:

$$EYR = \frac{E_{output}}{E_{input} + E_{BOS}} \qquad (2)$$

So, it's clear that the EYR is a dimensionless number. In some references [27], in order to calculate the EYR, the amount of electricity generation of the power plant during the first year, is multiplied by its total lifetime and replaced with the output energy (E_{output}) in nominator, which has some error. Because of the output power of all kinds of power plants over time have a downward trend. Therefore, it is suggested in this paper that the mentioned descending trend should be considered in calculating of EYR. The calculation of electricity production of this 7 MW photovoltaic power plant over its entire 25 years lifetime, with annually 0.5 % decreasing in its efficiency [25], has been considered. So, EYR for mentioned PV power plant is calculated as follows:

$$EYR = \frac{1{,}063{,}534{,}783}{248{,}832{,}000} = 4.27$$

4. Conclusions

In this paper, both CO_2 emission and EPBT for a 7 MW photovoltaic power plant in Hamedan province, Iran, were investigated. The environmental estimation was performed by RETScreen software. The results could be summarized as follows:

1- This PV power plant, could mitigate of emissions 5,362.3 t CO_2, annually, compared with a natural gas based power plant. In other words, 12470.4 barrels of crude oil not consumed.

2- In comparison with an oil based power plant, the mitigation of 10,068.4 t CO_2 emission or 23,415 barrels of crude oil not consumed, were estimated annually.

3- By considering the components of this 7 MW PV power plant, the Energy Payback Time is estimated about 5.5 years.

4- Beshik-Tappeh PV power plant can generate more than 4.2 times the energy it generates for its own production.

Acknowledgements

These and the Reference headings are in bold but have no numbers. Text below continues as normal.

Nomenclature

EPBT	Energy Payback Time
EYR	Energy Yield Ratio
BOS	Balance of System
PV	Photovoltaic
GHG	Greenhouse Gas

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